Security of Front End Beam Cutoff Devices

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When a beam cutoff request is processed by the Front End, two actions are instituted: removing the acceleration potential from the ion source body, and shutting off the r.f. excitation of the RFQ. This note analyzes the mechanisms that result in the shutoff of the beam emerging from the Front End systems.

1. Beam shutoff by removal of the acceleration potential from the ion source body

The ion source generates an H^- beam that is accelerated from the ion source body by the extractor electrode, and then is focused through a set of two einzel lenses. The energy of the beam at the RFQ entrance is, within a few electron volts, equal to the potential difference between the RFQ, which is at ground potential, and the potential of the ion source body, nominally at -65 kV.

Particle simulations show that the RFQ will not accelerate beam to full energy if the input energy to the RFQ falls below 11% of the nominal injection energy, or 58 keV. The beam will emerge from the RFQ at near the injection energy for injection energies significantly lower than 58 keV, but the RFQ design codes are not optimized to give an accurate output energy spectrum at operation conditions this far removed from nominal. The DTL will not accelerate beam whose input energy is more than a few percent lower than 2.5 MeV.

If the ion source body potential goes to zero (ground), and the rest of the lenses in the LEBT remain at their operating potentials and the plasma is still excited by r.f., beam will be extracted from the source by the extractor electrode, which is nominally +16 kV from ground. The two einzel lenses operate nominally at -45 kV, and the power supplies are unipolar, meaning that they would not put a positive potential on the lenses. If either of the two einzel lenses is grounded or negative, the H- beam will be repelled back to the ion source. Both lenses would have to attain a positive potential to allow the beam to proceed as far as the RFQ. Beam deposited on the lenses themselves could drive them to either polarity, depending on the magnitude of secondary electrons knocked off the lenses, but only to low voltage. With a secondary emission coefficient less than 1.0, beam impacting a lens would drive it negative, repelling the beam back to the ion source. The only credible scenario driving both einzel lenses positive would be a short-circuit to the extractor lens, a highly unlikely event for *both* lenses. Even so, the power supplies connected to the extractor lens or the two einzel lenses are incapable of supplying at least 58 kV to the lenses. Therefore, no credible scenario will cause the beam to be delivered at an energy above 58 keV with the 65 kV supply disabled.

Even if the beam makes it to the RFQ, which is grounded, beam transported from a grounded ion source body by the unlikely events described above, would enter the RFQ at zero energy and not be accelerated.

Another mechanism to consider is the production of a positive ion beam by double charge exchange somewhere in the LEBT and further acceleration by the RFQ to full energy. With the ion source at ground, the beam may have an energy of 16 keV at the extractor electrode. If double charge exchange converts at 16 keV H^- to a 16 keV H^+ beam at that point, then it would be further accelerated through the einzel lenses, achieving an energy of up to 61 keV in the lenses. However, upon reaching the grounded RFQ, the beam energy is again 16 keV, and it would not be further accelerated in the RFQ.

Focusing mismatch in the LEBT for a beam at other than the nominal energy in each lens will mismatch the beam into the RFQ, reducing any transmission to further below that of a properly matched beam.

The conclusion is that, if the ion source body is at ground, no credible mechanism will result in the acceleration of either H^- or H^+ to full 2.5 MeV energy by the RFQ.

2. Ion source operational but RFQ excitation removed

To accelerate beam by alternating (r.f.) fields, the beam must be bunched and then the beam velocity must match the phase velocity of the fields in the accelerating structure.

In an RFQ, the transverse strong focusing is provided by the quadrupole time-varying electric field. The betatron phase advance per focusing period is energy-independent in this configuration, which allows beam of energy significantly different from the design energy to be transversely focused by the structure. However, the bandwidth of the focusing passband in a FODO focusing scheme is limited, as the matched envelope size increases as the focusing strength decreases due to decreasing r.f. excitation of the RFQ structure. Eventually, the transverse phase space acceptance of the FODO channel decreases to the limit of the geometrical acceptance of a long channel with a small transverse cross section when the excitation goes to zero.

The bunching and acceleration of the beam is much more sensitive to the level of r.f. excitation of the structure than is the transverse focusing. After adiabatic bunching, the beam bunch is accelerated in a stable region of longitudinal phase space (the separatrix) that contains a stable fixed point around which longitudinal (synchrotron) oscillations occur.

With the parameters chosen for the SNS RFQ, the stable longitudinal phase space volume (the bucket) exists when the fields in the RFQ are at least 86% of operational gradient, reflecting a stable phase in the accelerating section of -30° (cos 30° = 0.866). At field levels of less than 86% in the RFQ, the accelerating bucket does not exist, and the beam will be only slightly accelerated in the adiabatic bunching section and then the energy spread in the accelerating section will increase slightly.

If the r.f. excitation for the RFQ is completely removed, no acceleration will take place, and any beam presented to the RFQ entrance will be transmitted only within the geometric acceptance of the RFQ. The RFQ has a length of 3.72 meters, and a geometric aperture radius of 0.35 cm. The geometric acceptance of the RFQ in each plane is 0.42π cm-mrad, at the 100% acceptance contour, or approximately

0.1π cm-mrad rms unnormalized. At an input beam energy of 65 keV, or $\beta = 0.012$, the normalized rms geometric acceptance is then 0.0012π cm-mrad in each plane.

At normal operating gradient, the RFQ acceptance is approximately 0.03π cm-mrad in each plane, so the ratio of acceptance in *both* transverse planes to a 65 keV beam is very approximately $(.0012\,\pi / .03\pi)^2 = 0.16\%$. This indicates that the RFQ with no excitation will not accelerate a 65 keV H- beam at its entrance, and that only a very small fraction of the input beam will emerge from the RFQ, all of it unaccelerated. A very small fraction of this already weak unaccelerated beam will be transmitted through the MEBT. As the energy is much lower than the 2.5 MeV MEBT design energy, the MEBT transmission will be low. As the energy is much less than the 2.1 MeV neutron production threshold in copper, no neutrons will be produced.

3. Beam abort time

The ion source body potential is provided by a -65 kV power supply. The power supply selected for operation at ORNL includes a large energy storage capacitor connected to the ion source through a series IGBT switch capable of interrupting the 65 kV potential in less than a microsecond. However, the distributed capacitance on the ion-source side of the switch may be as high as 5000 pF, which would result in as much as a few hundred microseconds of accelerated beam from the RFQ for the worst-case conditions. If a faster shut-down time is required, a shunt IGBT switch may be provided, shutting down the accelerated beam in less than 1 microsecond.

The RFQ will stop accelerating beam when the gradient falls below 86% of nominal accelerating gradient. The equivalent loaded circuit Q is about 3300, and when r.f. excitation is removed, the RFQ gradient will decrease below accelerating gradient in less than 4 microseconds.

4. Failure mechanisms

If the mains power is supplied to the 65 kV ion source power supply and to the 402.5 MHz r.f. amplifier to the RFQ through reactor-grade qualified primary breakers, the failure to stop beam will be given by the failure probability of the primary breakers to open.

However, the power supplies store some energy, and if only the primary breakers are tripped the beam shut-down time may be larger than the times given above, depending on the energy stored in the power supply components. If, in addition to tripping the primary breakers, some of the above-described techniques are used, the beam shut-off time can be reduced. However, there are failure mechanisms that may limit the shut-off time to that of tripping the primary breakers themselves. The stored energy in the large power supply energy-storage capacitor will allow beam to be generated until the capacitor is discharged to the point where the RFQ will not accelerate the beam. This may take as long as 330 milliseconds, allowing up to 20 beam pulses to be passed through after the primary breaker has been tripped.

The 65 kV series switch for the ion source may not open upon request. The failure mode for IGBT switches is to fail shorted. A large redundancy of IGBT units will be installed to alleviate this, but it is possible that eventually enough IGBT units will fail, and the ion source will continue to supply beam as described in the above paragraph for up to 20 1-millisecond pulses until the power supply energy storage capacitor discharged to below 58 kV.

The modulator that controls the r.f. amplitude to the amplifier supplying the RFQ may fail to cut the r.f. excitation off, so that the r.f excitation may not stop when requested. In this case, the stored energy in the klystron power supply may supply power for a while after the primary breaker is opened. The selected klystron power supply configuration uses IGBT switches supplying high-frequency a.c. to a three-phase high-voltage rectifier. It is inherent in the design of the equipment that the stored energy in the high-voltage ripple filter is low enough that the high voltage will fall in a few tens of microseconds to the point where r.f. will no longer be generated if the IGBT chopper pulse is interrupted. The stored energy in the filter capacitors for the a.c. line rectifiers is larger, and may result in r.f. being generated for a few milliseconds after the opening of the primary a.c. breaker if the chopper pulse is not interrupted.

In no case is it conceivable that a 2.5 MeV beam will be present at the exit of the Front End system for more than 500 milliseconds after the primary power is removed from either the ion source power supply or the r.f. power supply for the RFQ. Depending on actual circuit values once construction is complete, the actual time may be significantly less, but not longer.